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14. ABSTRACT During year one of the Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery (ACMI-SATS) project, the research team developed a testbed that allows for testing and evaluation of hypotheses related to tele-surgical robotic human-centered surgeon interfaces, cognitive workload, efficiency and situation awareness. The ACMI-SATS testbed includes both physical surgical robotic capability and simulation environments to maximize the efficiency of system development. We will complete the testbed hardware and software in year two of the project and complete a series of evaluations of ACMI-SATS augmentations by our research staff. The purpose of this project is to complete an ACMI-SATS testbed for use in future studies focused on development of optimal tele-surgical, tele-mentoring and remote operations technologies and methodologies for both military and civilian applications.					
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## Introduction

Robotic tele-surgery is a promising application of robotics to medicine, aiming to enhance the dexterity and sensation of minimally invasive surgery through use of millimeter-scale robotic manipulators under control of the surgeon. Current interfaces do not enable the surgeon to fully exploit his capabilities and may lead to underutilization of potential capacities offered by robotic tele-surgery in the future. In an attempt to advance the state of the art in the field of human-machine interface (HMI) and of the properties of sensory substitution, the Florida Institute for Human and Machine Cognition (IHMC) initiated a new project called Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery (ACMI-SATS). Its purpose is to improve the effectiveness of tele-surgery in military, as well as civilian applications by improving the sensory experience and the control input system using HMI principles to reduce surgeon cognitive workload as well as surgical errors.

## Body

The use of teleoperated surgical (tele-surgical) laparoscopic robotic systems is rapidly becoming the standard of practice for a number of surgical procedures. This technology reduces surgical trauma to the patient, lowers postoperative complications, improves surgeon ergonomics, reduces effects of surgeon motion tremors and enables the performance of novel techniques (e.g., the end effector can perform actions that a human appendage cannot; such as locking in position or rotating through more than 360 degrees). These “surgery by wire” systems can even remove the need to transport the patient to the surgeon’s location. Hirshauer (1991), however, notes that endoscopy separates the eye from the hand of the surgeon, and this isolation prevents the surgeon from perceiving useful kinesthetic feedback from direct interaction with the tissues present in traditional “open” procedures. Additionally, the reliance on video displays creates a visual information flow bottleneck. This increases the visual workload, which can lead to increased surgical errors, longer intraoperative sessions (with accompanying increased risks from anesthesia) and decreased number of procedures performed in a given time period. Technological systems that utilize visually dominant displays such as those used in virtual environment (VE) simulation and training have shown improved user task performance when tactile sensory information is combined with visual information (Briggs & Srinivisan, 2001; He & Agah, 2001). Virtual reality (VR) training systems have been developed to bring VE simulation to surgical training (Satava, 1995; Gallagher et al., 2005). Kinesthetic and haptic signals in surgical applications are critical, and prior work with VEs has shown that errors increase without realistic multi-sensory interactions (Cohn et al., 2000). Conversely, combining multiple sensory modalities (visual, spatial audio and tactile) has been shown to improve performance and situation awareness in complex dynamic tasks (Raj, Kass & Perry, 2000; Diamond et al., 2003; Olson et al., 2004; Erikson et al., 2008; Fuchs et al., 2008; Merlo, Gilson & Hancock, 2008).

Telerobotic systems such as the da Vinci<sup>®</sup> S HD (Intuitive Surgical, Sunnyvale, CA) already must employ torque, position, velocity and strain sensors used to maintain accurate closed-loop servomotion. Beyond control loop error based force-feedback, however, presentation of these data streams in raw form would not provide the requisite sensory data needed to enhance the surgeon’s experience. The addition of high definition stereoscopic visual displays can provide sufficient cues to create a visual perception of haptic feedback (Hagen et al., 2008). The sensory experience, however, still lacks the richness and subtleties available during open procedures and decrements procedural consistency, workload and operative efficiency (Tavakoli, Patel & Moallem, 2005; Zhou et al., 2008). Moreover, these systems require that the surgeon remain seated, head down at a control console to perceive the three dimensional video and use the fixed hand controllers. While this compares favorably to standing astride an operating table using laparoscopic instruments, the most favorable ergonomics would remove all restricted motion, posture and positioning of the surgeon. This would allow

telerobotic surgeon to move freely during a procedure to reduce fatigue and potentially perform more procedures in a given time frame.

In the military medicine domain, tele-surgical systems have the potential to revolutionize combat casualty care by bringing definitive surgical trauma care to the wounded servicemember without placing surgical specialists in harm's way. Current technology developments such as the United States Department of Defense (DoD) Defense Advanced Research Projects Agency (DARPA) Trauma Pod (Figure 1) seek to further reduce the time to delivery of surgical intervention by installing a complete tele-surgical system into robotic vehicles (Burnett, 2007; Satava, 2005a, 2005b). These Trauma Pods could be remotely driven to wounded soldiers in the field, providing an opportunity to treat severe wounds within the "golden hour" following injury (Pueschel, 2006). Deploying a fleet of such vehicles to a theater of operations would provide maximum benefit by providing the potential for immediate care to multiple wounded servicemembers with polytraumatic injuries following, for example, a detonation of an improvised explosive device (IED). In such a scenario, a small team of surgical specialists (e.g., orthopedic, cardiovascular, neuro, general/trauma surgeons, etc.) could stabilize, and possibly provide definitive care to, the maximum number of casualties if they could easily and safely handoff control of the robotic system between each other as needed. Because there would be no cross contamination between patients (or need to scrub or change sterile garments), the trauma team could manage the surgical needs of multiple patients more effectively than in current practice. Experience with other robotic systems, such as unmanned aerial vehicle (UAVs), however, has shown that the addition of robotic technology to a given mission can actually adversely increase manpower requirements.



**Figure 1:** DARPA Trauma Pod Concept (lead by SRI International) loading a wounded servicemember (left), evaluating the trauma (center) and performing surgery (right). Images downloaded from: <http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=364>, and [http://brl.ee.washington.edu/Research\\_Active/Surgery/Project\\_09/Project\\_09.html](http://brl.ee.washington.edu/Research_Active/Surgery/Project_09/Project_09.html)

The addition of high definition (HD) stereoscopic visual displays to robotic surgery systems provides an initial step toward improved sensory interface design. However, lack of haptic feedback in endoscopy, can lead to surgical errors such as tearing of tissues, broken sutures and hemorrhage, especially in delicate or intricate procedures (Bethea et al., 2004; Vassiliades, 2006). One approach to enhancing haptic feedback embeds tactile force reflection transducers on the fingertips in the surgeon console hand controllers (Figure 2) to provide a reflection of the force applied by endoscopic graspers capabilities (Morimoto et al., 1997; Bar-Cohen et al., 2001; Tavakoli, Patel, & Moallam, 2005; Culjat et al., 2008). While this technique has demonstrated improved surgical technique (reduced grasping force), the surgeon's auditory and tactile sensory capabilities remain under utilized while his or her visual sense remains highly task loaded. Alternate haptic interfaces that provide end effector force feedback indicate resistance to commanded movements proportionally and complement the visual display to reduce workload (Wagner, Stylopoulos, Jackson & Howe, 2007). However, the narrow field of view provided by the endoscope negatively impacts situation awareness (SA) by limiting perception of complex spatial relationships within the body cavity. This loss of SA may lead to

inadvertent incursion into sensitive structures following camera orientation changes or movement of internal organs. These haptic approaches borrow concepts from the VE and VR worlds that place a high premium on *presence* (the convincing sense of perceiving as if physically in the VR or VE). In contrast, tele-surgery must place the highest premium on effective *treatment* of the patient by optimizing perception of patient state to the surgeon, rather than presence. Because the feedback generated by the sensors in the operative field is no longer directly coupled to the surgeon's hands (either through direct contact with the tissues or indirect contact via rigid laparoscopic instruments), opportunities now exist to utilize other sensory substrates. In fact, some actions in surgical robotic manipulation can cause the surgeon to make inadvertent hand movements due to haptic force feedback errors (Tavakoli, Patel, & Moallem, 2005). Unlike classic VE/VR approaches to haptics in tele-surgery, these alternative display technologies could complement or supplant traditional haptics without affecting or interfering with the motion of the primary control input mechanism. For this discussion, haptics will refer to telepresence related kinesthetic sensory interactions while tactile will refer to more general or abstract tactual interactions.



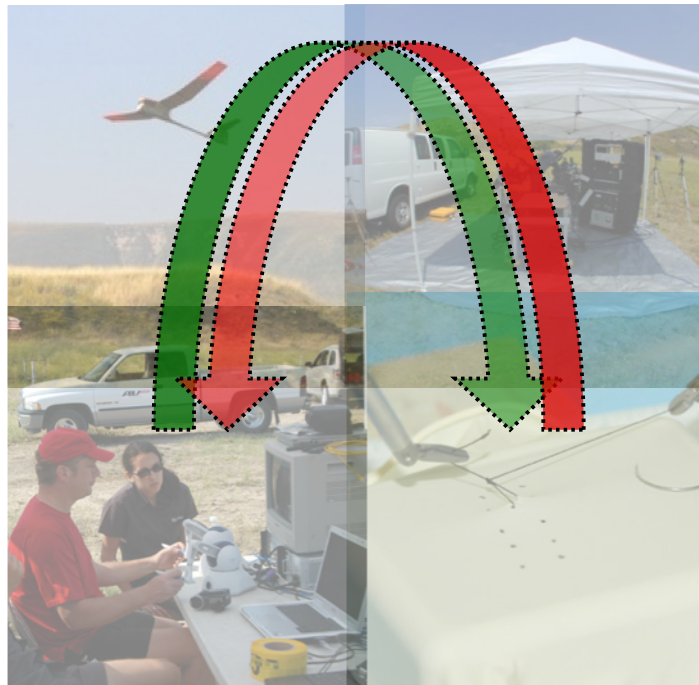
**Figure 2:** (left) Electro-rheological fluid (ERF) based haptic surgeon hand interface (Bar-Cohen et al., 2001); (center) Force transducer fitted to endoscopic grasper; (right) Pneumatic haptic finger tip display (Culjat et al., 2008) integrated with da Vinci<sup>®</sup> hand controllers.

Perception takes place in the brain, not at the end organ (Bach-y-Rita, 1972); therefore, the brain can learn to reinterpret the meaning of signals from specific nerves (e.g., from tactile receptors) given appropriate self-generated feedback. This forms the basis for interfaces that can non-invasively and unobtrusively use alternative sensory pathways to provide information. This means that the information displayed does not necessarily need to represent the underlying data at high resolution, rather abstract representations of the sensory environment information can provide sufficient data for operator decision making and improved SA (Raj, Kass & Perry, 2000). Such sensory substitution mechanisms have been demonstrated in tele-surgical applications (Kitagawa et al., 2005) and exploit the plasticity inherent to the brain and nervous system, which supports both long term and short term anatomical and functional remapping of sensory data (Finkel, 1990; Walcott & Langdon, 2001). Therefore, a new class of interfaces could be incorporated into the tele-surgical surgeon interface. Using alternative tactile and spatial audio displays that provide higher level representations of data could provide metadata information or data that a surgeon could not physically sense directly even when performing an open procedure.

Divorcing the surgeon's sensory perception from direct mechanical linkage to the patient, the operative field, and the surgical instruments could also enable a paradigm shift in tele-surgical methods. Laparoscopic instruments were initially developed as extended versions of their counterparts used in open procedures (e.g., extended length scissors, needle drivers, etc.); even though the scaling induced poor ergonomics, familiarity with the older tools existed. Likewise, current tele-surgery systems utilize tools that mimic the laparoscopic instruments, replacing the direct mechanical connection with an electronic one. The functional capabilities (e.g., degrees of freedom) of the robot end effectors (such as the da Vinci<sup>®</sup> EndoWrist<sup>®</sup>) exceed

those of laparoscopic instruments and human hands. Advances in head mounted displays and motion capture from the commercial sector can now allow both freedom of movement and high resolution stereoscopic visual perception without confining the user to a fixed console. Motion capture could translate movements that match the scale and trajectories of normal (real-world) kinesthetic interactions, as well as enable the use of motion gestures to accomplish supervisory-controlled actions to take advantage of the higher capabilities of modern robotic surgical systems. Because kinesthetic perception includes both self-perception (proprioception) and perception of changes in the environment (Hannford & Venema, 1995), proprioceptive sensations could disambiguate abstract sensory substitution displays of end effector motion. The full use of arm movements (versus hands only) could provide more accurate mapping to the degrees of freedom available in modern surgical robots.

Clearly, adding additional sensory channels would increase the volume of information flow to the surgeon. The human brain, however, has developed to make use of multi-sensory inputs in the natural world, which provides a richer sensory environment than most man-made systems. This increase information transduction will also markedly increase the bandwidth requirements for data flow between the robot (e.g., installed in a Trauma Pod) and the remote surgeon (Hannford & Venema, 1995). Recent DoD projects such as the High Altitude Platforms Mobile Robotic Tele-surgery (HAPsMRT) (Broderick, 2006; Rosen & Hannaford, 2006) and the Smart Codec with Tele-surgery Capability (Energid Technologies, Cambridge, MA), respectively, have developed methods that use unmanned aerial vehicles to reduce the radio frequency signal lag between the surgeon and the robotic end effectors and to develop efficient algorithms for transmission of data (Figure 3).



**Figure 3:** High Altitude Platforms Mobile Robotic Tele-surgery (HAPsMRT) technology demonstration using real time data compression and a UAV data relay to provide haptic interactions in tele-surgery (Broderick, 2006). Surgeon movements (left, lower) are relayed via UAV (left, upper) to a surgical robot (right, upper) with force feedback provided through haptic enabled hand controllers to accomplish suture task (right, lower).

When processing and inter-pretng tactile data, specific traits of human sensation and cognitive processing such as adaptation, habituation, or satiation to durative stimuli may interfere with perception of persistent tactile and other sensory stimuli. Adaptation occurs when a signal persists for many minutes (e.g., the tactile sensation of wearing a watch is automatically filtered out by the peripheral and central nervous system). Habituation occurs when a durative signal repeats periodically (e.g., a ticking clock) and is no longer perceived. Satiation, also the product of prolonged stimulation, produces specific spatial distortions (Cholewiak, 1976), perhaps based on transient plasticity (Whitsel et al., 1989; Merzenich, Recanzone, Jenkins,



Allard & Nudo, 1988). These are known issues with known solutions currently implemented in IHMC's Adaptive Multiagent Integration (AMI) software (e.g., modulation of waveform characteristics of persistent cues) that mitigate their effects. AMI agents can also generate sensory illusions, such as spatial audio, the saltation rabbit illusion (Geldard & Sherrick, 1972, Geldard, 1975; Bremer, Pittenger, Warren, & Jenkins, 1977) and spatial summation (Craig, 1968). Recent studies have confirmed that tactile illusions are processed at the cortical level as if they were real; that is, no differences between illusory and veridical tactile stimulation patterns manifest in functional magnetic resonance (fMRI) scans of the human brain (Blankenburg, Ruff, Deichmann, Rees & Driver, 2006). Therefore, tactile illusions could improve the perception of a tactile signal beyond the physical resolution a given display.

Prior research by this team and others with tactile sensory substitution has shown that the brain is capable of integrating the information from an artificial receptor, arriving via a brain-machine interface (BMI), in a perceptual experience that depends upon the nature of the information gathered by the specific artificial receptor (Bach-y-Rita, 1972, 1995; Bach-y-Rita, Collins, Saunders, White & Scadden, 1969). The BrainPort® device (Wicab, Inc., Madison, WI) provides information to the brain through electrotactile stimulation of the tongue (Bach-y-Rita, Kaczmarek, Tyler, & Garcia-Lara, 1998). Receptors on the tongue surface are uniquely qualified to receive electrical impulses because of the density and sensitivity of nerve fibers at this site, the electrolyte (saliva) that allows it to receive and maintain electrical contacts, and its proximity to the brainstem, minimizing perceptual lag. With the highest resolution device currently available, an approximately 25x25 tactile image (some are not active) is created by a sequence of pulses presented at a rate of 200 Hz. The amplitude value (voltage) of the pulse sequence or 'burst', updated at 50 Hz, varies with the grayscale level of a video image. The participant controls the overall intensity (voltage) level, which does not exceed 15VDC. The second novel tactile interface, the VideoTact, is an electrotactile interface placed on the abdomen that exploits the larger surface area of the abdomen to provide a larger display area. While the density of torso sensory receptors is lower than the tongue, placing a high-resolution display (i.e., 24x32) on the abdomen allows for rapid perception of motion of objects (Bach-y-Rita et al., 1969) and can be worn discretely under the user's clothing. An electrolyte gel is used to ensure electrical contact with the skin.

A number of recent and ongoing studies with the BrainPort® have shown that blind individuals can recognize elements of standard eye charts (Sampaio, Maris & Bach-y-Rita, 2001, Kupers, Sampaio, Moesgaard, Gjedde & Ptito, 2003) and labyrinthine defective individuals (those with inner ear balance disturbances) can dramatically improve balance (Tyler, Danilov & Bach-y-Rita, 2003). This requires that the user have control of the movements of the sensor in order to self-generate feedback to reinforce the novel sensory stimuli. In the absence of the sensory-motor loop, we have observed that the sensory stimulation through a tactile array is perceived as a purely tactile experience localized to the body part in contact with the array. Laboratory studies and operational test and evaluation of the Tactile Situation Awareness System (TSAS) and other tactile displays have shown that individuals rapidly localize and respond to encoded tactile cues presented on the torso and limbs (Calhoun, Draper, Ruff & Fontejon, 2002; Diamond, Kass, Andrasik, Raj & Rupert, 2003; Raj, Kass, & Perry, 2000; Sarter, 2001; McGrath, Estrada, Braithwaite, Raj & Rupert, 2004). This forms the rationale for utilizing self-generated natural movements of the hands, arms and body to control robotic systems.

Natural motion gesture-based control reduces the workload and learning associated with standard joystick/button input devices and providing low latency feedback through haptic interfaces allow precise control of an external system with minimal training time. Blinded servicemembers learned to stabilize and manipulate the tactile image with their prosthetic eyes



within 10-20 minutes, demonstrating that the tactile feedback does not need to be presented through the hands for accurate perception and control of a dynamic action. In year 2 of this project, we will evaluate performance of specific tasks such as percutaneous needle insertion, for example, initiated with a gestural command, and monitored and adjusted through a tactile or auditory presentation. We envision that one could switch between robotic platforms (i.e., dV-Trainer and Zeus®), between actual patients in different Trauma Pods, or between different surgical instruments (i.e., simulating an automated tool exchanging mechanism) using gestures. Simple combinations of movements such as turning to face a different direction accompanied by specific hand movements could provide an efficient method of hand-off or change of procedure. IHMC has more than 30 Zeus® surgical instruments. In this project, we have used gesture recognition agents in AMI to recognize gestural requests to lock robot joints during specific tasks, such as changing the camera angle or robot arm selection. Further gestures will be implemented, such as performing an instrument change-out displaying the interpreted request to an assistant who will manually perform the change, mimicking an automated tool exchange.

Obtaining high gesture recognition accuracy requires the ability to accurately sense the position and configuration of a user's hands, limbs, head and torso. IHMC has developed custom software implemented in AMI that allows rapid, accurate detection (within a few millimeters) of relative positions of body components, estimation of center of gravity, ground reaction force center of pressure, and estimation of dynamic stability. This system incorporates data from a custom built wireless, wearable force sensing insole system with 132 load cells per foot (Pressure Profile Systems, Los Angeles, CA) and a full body/limb/head wireless, wearable motion capture system (ShapeWrapIII, Measurand, Inc, Fredericton, NB) that has been integrated into the ACMI-SATS prototype to provide the user with sense of proprioception and interaction with the ground through the haptic interfaces (Figure 4).



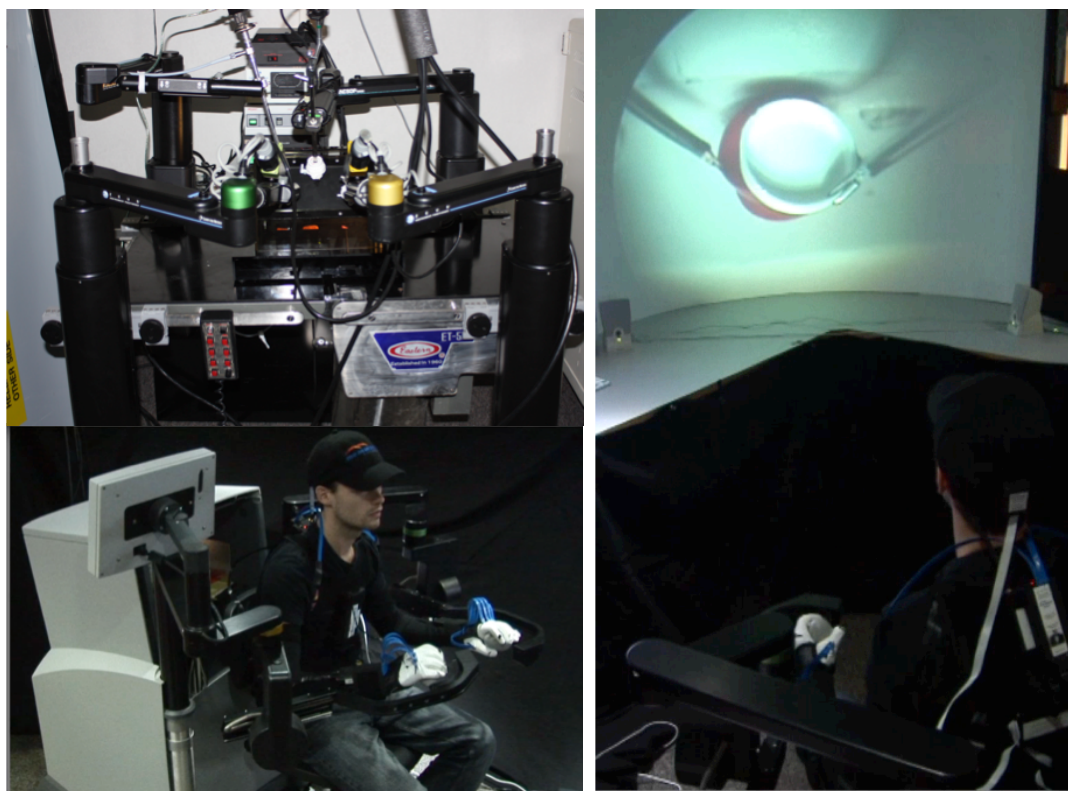
**Figure 4:** Body position (inset) tracked with ShapeWrap system using IHMC's AMI architecture. Box projected under avatar indicates stable platform for a given stance.

In addition to the loss of haptic and tactile sensation rising from the transition from open to endoscopic procedures, the surgeon also loses the significant kinesthetic feedback associated with gross motor movements. Because robotic systems (unlike laparoscopic systems) can provide motion scaling kinesthetically rich, large arm and body gestures can be translated into precise movement of surgical instruments. Recently, IHMC and its research partners demonstrated gestural control of fine movements of a robotic arm simulator and stabilization of visual imagery represented tactually to recently blinded servicemembers. In the former application, the operator controls the National Aeronautics and Space Administration (NASA) Basic Operational Robotics Instruction System (BORIS) software robot (Gilliland et al., 2005) with natural arm and hand movements. In the latter, extraocular musculature controls the user's prosthetic (glass) eyes which are rapidly stabilized utilizing movement cues sensed in the tactually presented image using a BrainPort® interface (Figure 5).



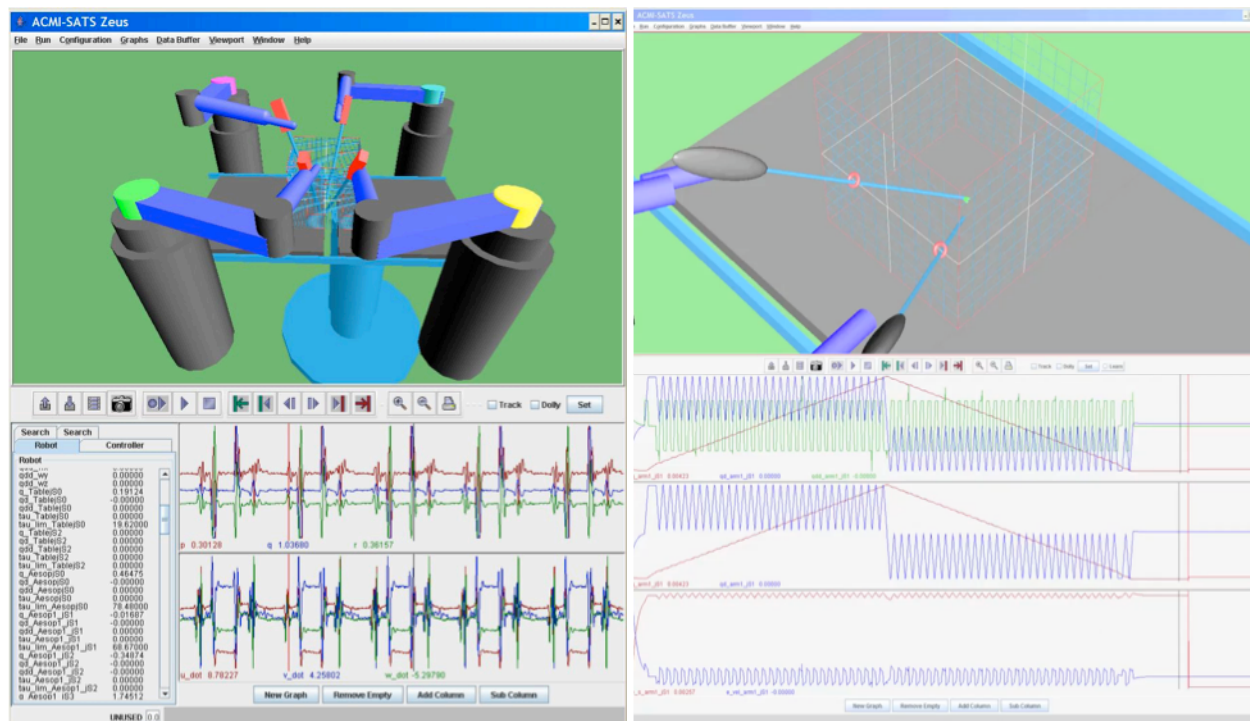
**Figure 5:** (left) Gesture based controller for robotic arm simulator. (right) *Status post* binocular enucleation, a servicemember uses his prosthetic eyes to control a tracking reticle on the screen with tactile (tongue based) display of area displayed inside the reticle (near user's finger).

The first quarter activities primarily consisted of purchasing required equipment, initiating development of a simulation environment for our existing surgical robot hardware (Zeus, Computer Motion, w, CA), and assembling of the components in the laboratory space. We acquired two additional Aesop arms that are functionally equivalent to Zeus arms (aside from the micro wrist). This allows us to implement a four-arm solution similar to the da Vinci<sup>®</sup> system, and a spare for testing hardware modifications (Figure 6).



**Figure 6:** Left, Top- IHMC ACMI-SATS Zeus configuration with four robot arms. In the center of the operating table, a plexiglass "patient simulator" provides a closed environment for endoscopic activities. Left, Lower- The Zeus can be controlled by the stock control input devices, or with more natural movements using motion capture. Right- Human scale projected imagery from the Zeus testbed.

The virtual prototype of the Zeus robot was designed to test hypotheses before committing to physical hardware. The virtual robot was made in Java programming language, and was based on the functionalities of Yobotics Simulation Construction Set (Yobotics, Inc., Cincinnati, OH). The simulator created an accessible environment that allowed for rapid evaluation and testing of surgical concepts. The simulation (Figure 7) provides a physics-based graphical simulation of the robot arms that is kinematically accurate and allows development, test and evaluation of ACMI-SATS concepts prior to implementation on the hardware. The Yobotics SCS allows both simulated input and real world sensor inputs to drive the motion of the arms. Input signals and robot responses can be displayed in stripchart form and recorded. These recordings can then be played back at various speeds relative to real-time to fully explore response characteristics.



**Figure 7:** Left- Yobotics Simulation Construction Set implementation of IHMC's current Zeus-based ACMI-SATS surgical robot configuration. Top frame shows graphical model of configuration shown in Figure 1. Left panel provides a list of joints in the system and their orientations, torques, rates, etc. Lower panel shows strip chart representation of variables selected from the list in the left inset panel. Right- Simplified physics only model of two robotic arms with port reaction forces modeled.

The second quarter entailed integration of required hardware, continuing development of a simulation environment for our existing Zeus surgical robot hardware and testing of the components in the laboratory space. Using AMI, we have integrated our wireless full-body, wearable motion capture system (ShapeWrapIII) with our Yobotics simulation of the four-arm Zeus system developed in the first quarter. This simulation provides a physics-based graphical simulation of the robot arms that enables development, test and evaluation of ACMI-SATS concepts prior to implementation on the physical hardware. We updated 1970's era pen-plotter routines for "look ahead" operations that use the system model to smooth motion despite varying time steps. This feature would be useful in remote tele-surgical applications with intermittent communications or low bandwidth (e.g., TraumaPod). Figure 7 (right) shows an intermittent command signal (blue) being smoothed in to a smooth velocity using the look ahead algorithm. A MIDI control surface (BCF2000, Behringer International GmbH, Willich, Germany)

allows manual positioning of simulation parameters (such as friction, rates and joint positions). This mechanism also allows tweaking of offsets to match body movements to robot actions in the simulation. We have also completed our AMI integration of a 10.2 channel surround sound in the laboratory space. Lastly, our co-investigator, Thomas Vassiliades, MD, a minimally invasive cardiovascular surgery expert, traveled to IHMC to evaluate both the Yobotics simulation and the Mimic dV-Trainer system.

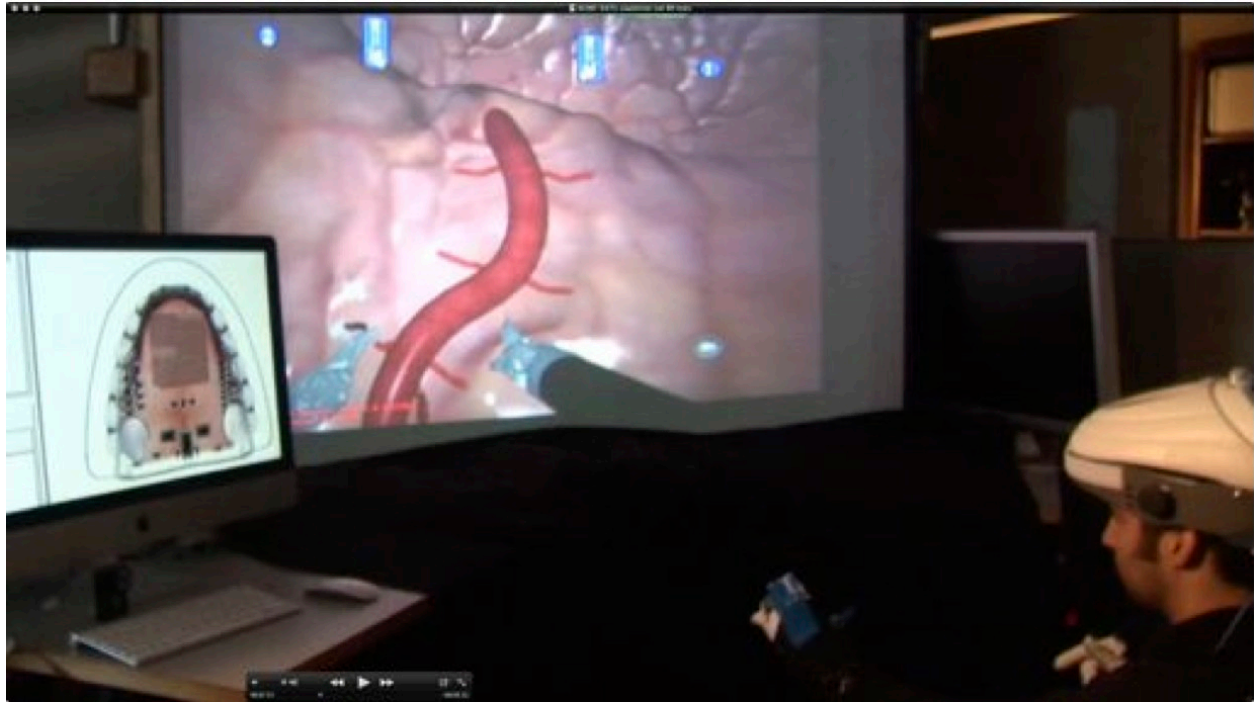
In the third quarter, we continued development of the simulation environment using Yobotics Simulation Construction Set for our existing surgical robot hardware. We modified the actual Zeus hardware, and implemented auditory and tactile interfaces for representation of Zeus data using our Adaptive Multiagent Integration (AMI) software, simulation of the four-arm Zeus system developed in the previous quarters.

We also added head tracking (OptiTrack, NaturalPoint, Inc., Corvallis, OR) to the control input stream to automatically change the point of view camera location with user head movement. This camera control mechanism provides motion parallax tied to the user's x, y and z axis head movements to create a dynamic viewpoint that supports intuitive user interaction. As the user moves toward and away, left and right, or up and down with respect to the screen, the camera system zooms in and out or shifts the view in the simulation appropriately to create an effective 3D viewing experience. Because drastic movements would affect system performance, and surgical tasks should be performed with lower dynamics, simple velocity cut-offs prevent unintentional motions from changing the view or moving the robot. We implemented this technique with our Yobotics based simulation in the third quarter and then integrated it with the Mimic dV-Trainer when we receive the updated code in the fourth quarter. We believe we can accomplish the same effect with real endoscopic video images by integrating a real time model creation capability (Tardif & Roy, 2005).

In the fourth quarter, we focused on integration of ACMI capabilities with the Mimic dV-Trainer through our AMI software using the same approach used with the Zeus/Yobotics simulation developed in the previous quarters. This includes direct control of the Mimic dV-Trainer arm position and orientation as well as closure of the end effector. Gestural movements of the fingers allow for selection of mode (e.g., lock position, clutch, activate electrocautery, etc.) and arm (e.g., arm two or three) without the need for foot-activated switches. Similarly, head movement-based control replaces the need to toggle between endoscope and arm controls (figure 8). The aforementioned parallax system, now integrated with the dV-Trainer, provides a point of view that moves in an intuitive fashion with the head such that moving forward or backward increases or decreases the zoom level, respectively. Vertical and horizontal motion causes the point of view in the simulation and changes the parallax appropriately to provide a convincing sense of depth. The camera can be locked (using a gesture) in a given viewpoint or moved continuously with the head (which provides a visual sensation similar to that of an open surgical procedure).

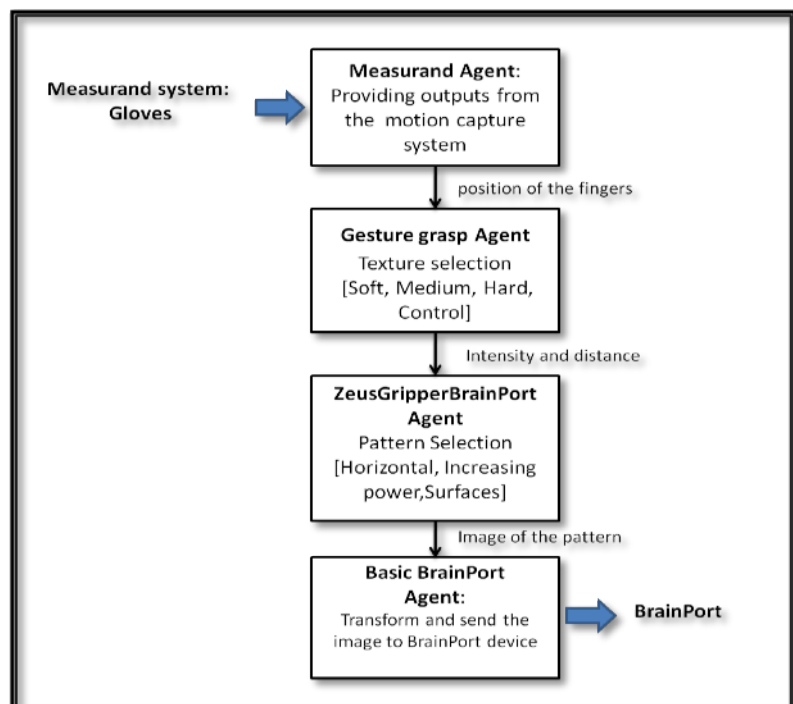
We developed a number of electrotactile symbologies for representation of the positions and forces on the end effectors as well as relative locations and forces on the robot arm shafts. The end effector information displays on the tongue using the BrainPort® device and shaft data displays on the abdomen via the VideoTact electrotactile interface. Both the BrainPort® and the VideoTact devices, as well as a 10.2 channel surround sound system were evaluated as potential sensory augmentation methods for surgical interfaces.





**Figure 8:** Mimic dV-Trainer imagery projected to a size that provides a reasonable approximation of the human hand and arm. Control via motion capture of hand and arm movements maps in a 1:1 ratio with onscreen robot movement. This allows for veridical kinesthetic and proprioceptive cues to augment visual information. Screen on left shows graphical representation of electro-tactile stimulus on the tongue that represents both closure angle (distance between tactile icons) and forces (intensity of stimulus) on the two active (right and left) grasper end effectors.

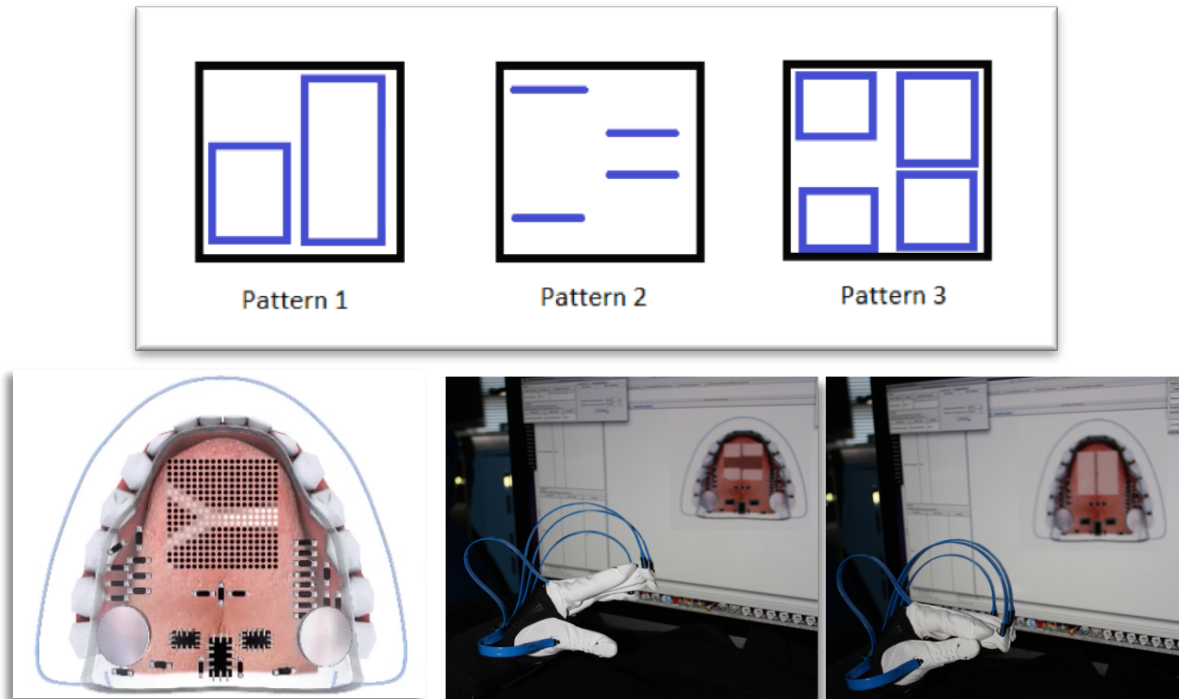
By using the AMI framework we have been able to couple a wireless, wearable motion capture system, the surgical analog environment and appropriate sensory feedback displays to improve the user experience. A flow chart of one ACMI-VAS set-up is shown below (Figure 9). This exemplar tracks hand and digit positions from a Measurand AMI software agent which is processed by the Gesture Grasp Agent to compute the distance between the fingers of interest (thumbs and indexes of each hand). This value drives the selection of the method of intensity level display: 1) Soft-the intensity first increases slowly when the grasper encounters an object and then more rapidly as the grasper closes (similar to the force



**Figure 9:** Flow chart of a full ACMI-SATS implementation for the Zeus surgical robot (see text).

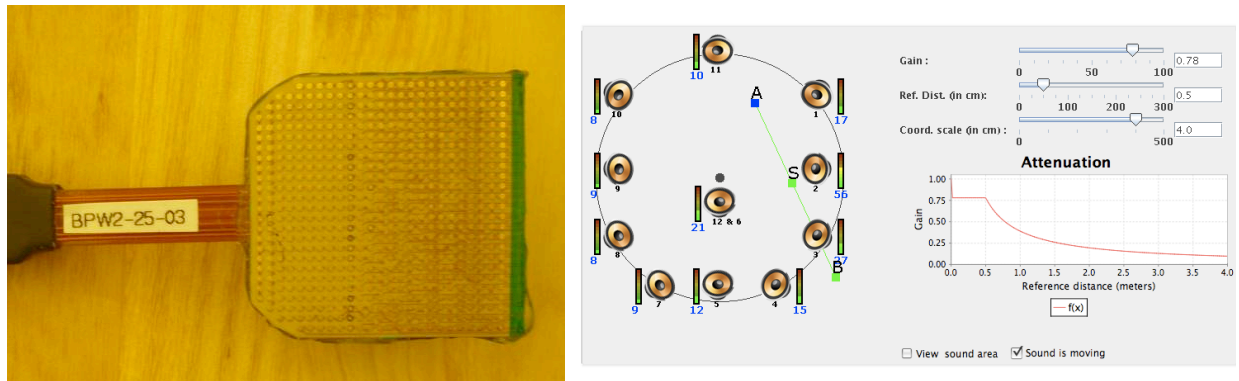
sensation when we squeeze a soft object); 2) Medium- the intensity remains directly proportional to the distance between the fingers (using a variable gain set before use); 3) Hard- intensity sharply increases as soon as the grasper contacts an object and 4) Isointensity- only grasper closure angle is represented, with intensity held constant.

The Gesture grasp Agent sends the current distance between the fingers and the current intensity value to the “Zeus Gripper BrainPort Agent”. The Zeus Gripper BrainPort Agent uses the values to create an image of the pattern of stimulation, which is then sent to the BrainPort Agent. The BrainPort Agent includes a graphical user interface (GUI) that provides visual feedback to the researcher regarding the user's stimulus (figure 10).



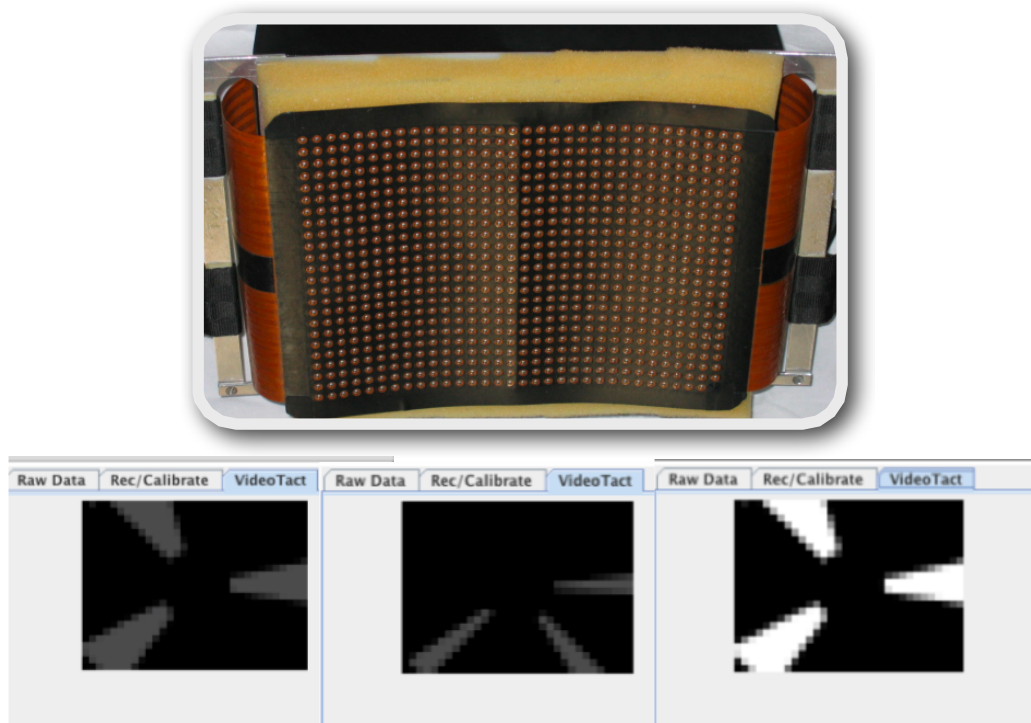
**Figure 11:-** Top Row- Three different symbolologies for representing grasper closure angle on the tongue. Bottom Row- Two approaches for end effector electrotactile representation. (*Left*) One open and one closed grasper (right grasper is closed firmly resulting in higher stimulus intensity). (*Right*) Alternate representation of tactile symbology.

Lastly, the BrainPort Agent converts the image into a grayscale intensity map that is delivered to the BrainPort® Intraoral tongue array (figure 12). We also prototyped a condition where the final software element transformed the image into surround sound (grasper closure angle and force represented by fore/aft sound position and tone frequency, respectively). In simulation evaluation activities, the intensities mapped onto the tongue gave the user a finer degree of control during manipulation of the objects with the graspers. In future activities surround sound will be assigned to represent audio sources (e.g., the sound of electrocautery activation will appear auditorily mapped to the relative location of the electrocautery end effector).



**Figure 12:** Left- BrainPort® Intraoral Device electro tactile tongue array (600 tactile pixels). Right- Surround Sound AMI agent that controls 10.2 sound system to place stimuli spatially in the audio environment.

To improve perception of the locations of the robot arms beyond the field of view of the surgeon, we added symbology to with the VideoTact to present the relative positions of the end effector shafts in screen coordinates (figure 13). Stimulation frequencies of 1Hz, 4Hz and 10Hz represented each arm when projected onto the user's abdomen. As was predicted beforehand, 10Hz greatly facilitated recognition. Experiments indicated that three moving arms were more difficult to differentiate effectively with this symbology, though one or two arms were easily recognized by a user. Further activities will identify optimum stimulus frequencies and symbology sets.



**Figure 13:** Top- VideoTact (ForeThought Development, LLC, Blue Mounds, WI) electro tactile abdominal display. Bottom- Graphical representation of robot arms relative to endoscope orientation. The tactile wedges represent the projection of the robot arm shafts outside the field of view of the camera back to the entry port. This allows the user to maintain awareness of arm positions, movements and forces that remain outside the field of view. The black rectangle at the center represents the camera field of view (projected visually).



A connection between the AMI system and the da Vinci® simulation system allowed for interactive simulation and testing of the full ACMI-VAS concept. Mimic Technologies, Inc., provided appropriate software hooks and documentation to enable AMI to interface to simulation variables including control inputs for and states of the shafts and the tips of the instruments, the positions of the camera, and the applied forces (pushing and pulling forces on tissues as well as grasping forces).

#### *Relationship to award Statement of Work*

At the end of the first year of the program, we have developed a multisensory interface that provides visual, audio and tactile displays as well as incorporates veridical kinesthetic and proprioceptive cueing. In addition, we have created a generalizable, intuitive control interface for surgical robots using motion capture and gesture detection to command the robotic system. Based on the original statement of work, we have completed the following tasks from Specific Aim # 1: Develop a multi-sensory interface to augment current visual and haptic interfaces that will include of spatial audio and tactile interfaces:

#### *Task 1. Modify IHMC Auditory and Tactile interfaces for tele-surgical application*

- 1a. Select tactile displays and body mounting locations
- 1b. Define intracorporeal orienting requirements
- 1d. Evaluate tactile and audio cueing representations
- 1e. Integrate software for spatial cueing

Task 1c. Define registration method for marking locations of organs and vessels was delayed due to logistics issues with the Mimic dV-Trainer and will be completed early in year 2. This will complete Task 1 and produce Milestone #1 (Spatial audio and tactile interface critical design review).

#### *Task 2. Integrate IHMC AMI software & Mimic dV-Trainer-Mantis Duo*

- 2a. Define interface over Ethernet
- 2b. Test transmission of dV-Trainer state variables over Ethernet to AMI
- 2c. Test transmission of AMI control input data variables to dV-Trainer
- 2e. Develop software interface to existing tele-surgical robotic end effectors

Task 2d. Develop hardware interface to existing tele-surgical robotic end effectors has taken longer than expected due to limited documentation on the Zeus robot. We have identified all the signals that represent the robot joint positions and forces and can issue control commands from an external computer interface. Integration with AMI will continue in year 2 and result in Milestone #2 (Complete software Ethernet interface definition and testing).

We have completed the following tasks from Specific Aim # 2: Develop a generic tele-surgical robot control input mechanism that allows use of normal kinesthetic hand and arm movements using motion capture and gesture recognition

#### *Task 3. Code software for natural movement control of ACMI-SATS*

- 3a. Define and integrate motion primitives for tele-surgical activities
- 3b. Bind coded motion primitives to dV-Trainer control input commands
- 3c. Code user interface
- 3e. Test and evaluate interface function with tactile and audio displays
- 3g. Test and evaluate gesture based commands in dV-trainer simulation

Tasks 3d) Code performance evaluation interface and 3f) Code finite state machine (FSM) algorithm for gesture recognition are progressing and will be complete in year 2 to reach Milestone #3 (ACMI-SATS system design complete).

#### *Task 4. Demonstration and evaluation*

##### 4a. Prototype system functional verification and testing

Tasks 4b) Demonstration and evaluation with subject matter expert Co-Investigator and 4c) Analyze results for presentation at the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) annual conference will occur in year 2 and will result in the Milestones 4 & 5 (Demonstrate ACMI-SATS system with simultaneous simulated procedures and draft manuscript for submission to Surgical Endoscopy, respectively)

#### **Key research accomplishments**

- We successfully integrated our AMI software architecture with a physical four arm surgical robot (Zeus) and with a commercially available tele-surgical simulation (dV-Trainer)
  - We created a physics-based kinematically accurate graphical simulation of the Zeus robot
- We integrated spatial audio, tactile and large format visual displays for improved surgeon situation awareness.
  - We have evaluated a number of electrotactile and auditory symbologies for representation of the positions and forces on the end effectors as well as relative locations and forces on the robot arm shafts.
- We have integrated a wireless full-body, wearable motion capture system (ShapeWrapIII) and head tracking (OptiTrack) to allow full freedom of movement for the surgeon.
  - We implemented gesture based control elements into the ACMI-SATS testbed to provide intuitive mode switching and tele-robotic system control
- We implemented a 1:1 scaling between arm and hand movements and the visual representation of the endoscopic view to ensure useful kinesthetic, proprioceptive and motion parallax cues.

#### **Reportable outcomes**

We presented our preliminary approach and results at the Aerospace Medical Association's 81<sup>st</sup> Annual Scientific meeting and submitted an abstract for review and possible inclusion in the 2011 SAGES Annual meeting (see appendix 1 for abstracts):

Raj, A. K. & Cameron, J. D. (2010). Multisensory Augmentation of Telemedicine Systems, *Aerospace Medical Association 81<sup>st</sup> Annual Scientific Meeting*, Phoenix, AZ.

Raj, A. K., Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V., Vassiliades, T. A. (2011, submitted) Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery. *2011 SAGES Annual Scientific Meeting*, March 30-April 2, 2011, San Antonio, TX.

#### **Conclusion**

During year one of the ACMI-SATS project, we developed a testbed that allows for testing and evaluation of hypotheses related to tele-surgical robotic human-centered surgeon interfaces, cognitive workload, efficiency and situation awareness. The ACMI-SATS testbed includes both physical surgical robotic capability (Zeus) and simulation environments (Zeus/Yobotics, da Vinci<sup>®</sup>/Mimic) to maximize the efficiency of system development. We will complete the testbed hardware and software in year two of the project and complete a series of evaluations of ACMI-SATS augmentations by our research staff. The completed ACMI-SATS testbed could be used for future studies and for development of optimal tele-surgical, tele-mentoring and remote operations technologies and methodologies for both military and civilian applications.

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## Appendices

## Appendix 1: Abstracts

Raj, A. K. & Cameron, J. D. (2010). Multisensory Augmentation of Telemedicine Systems, *Aerospace Medical Association 81<sup>st</sup> Annual Scientific Meeting*, Phoenix, AZ.

**Introduction:** Modern electronics, software and networking technologies have enabled the development of telemedicine capabilities that bring medical expertise to remote locations. Additionally, telemedicine enables telementoring to allow more individuals to benefit from interactions with expert practitioners. The aerospace medical community has embraced these novel concepts, which have the potential to dramatically improve delivery of care to deployed units or vehicles in flight. The available interfaces, however, provide primarily visual information with some additional verbal auditory data. This prevents the physician from experiencing the rich multisensory cues utilized in normal one-on-one patient or training interactions. Previously we have developed an anthro-centric multisensory interface (ACMI) system that can manage multiple types of data streams and display information to users via visual, audio and tactile.

**Methods:** The adaptive multiagent integration (AMI) software agent architecture was used to integrate video imagery, surround sound audio and tactile representations of information during telemedical simulations. This ACMI implementation provides typical video feeds with adjustable levels of visual graphic overlay. Multiple microphones capture spatial relationships of the auditory environment (represented using surround sound). Combined with tactile spatial orientations interfaces that provide perception of items outside the visual field provided by the camera, these displays improve user situation awareness (SA).

**Results:** Performance (time to complete, number of errors) improved for individuals when using telemedicine apparatus with ACMI vs. no ACMI enabled for a series of telemedicine relevant simulated tasks.

**Discussion:** Telemedicine holds great promise for use in aerospace environments. Augmentation with multisensory displays could enhance effectively and expand capabilities and applications without increasing user workload.

### *Learning Objective 1*

Current methods for multisensory interface implementations will be described.

### *Learning Objective 2*

Techniques for improving multisensory situation awareness without increasing system bandwidth usage will be discussed.

### *Learning Objective 3*

Effectiveness of multisensory interface in telemedicine applications will be discussed.

Raj, A. K., Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V., Vassiliades, T. A. (2011, submitted) Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery. *2011 SAGES Annual Scientific Meeting*, March 30-April 2, 2011, San Antonio, TX.

**Objective of Technique:** While telerobotic surgical systems augment minimally invasive surgery techniques and reduce surgical trauma, they increase surgeon workload by limiting sensory feedback. Unlike open or laparoscopic procedures, surgical robots isolate the surgeon from tactile, proprioceptive, kinesthetic and orientation cues, which provide non-visual inputs that help maintain situation awareness (SA). The robot control system, however, employs sensors for torque, position, velocity and/or strain sensors to maintain accurate closed-loop servomotion, which could help inform the surgeon's SA. Though sitting at a console compares favorably to standing astride an operating table using laparoscopic instruments, removing all restrictions on surgeon motion and posture would allow telerobotic surgeons to move freely and reduce both physical and cognitive fatigue. Lastly, the surgeon must change modes between control of primary instruments and any additional arms (e.g., third effector, endoscope, etc.), but current robot interfaces provide little, if any, feedback to help the surgeon maintain awareness of such changes.

The objective of the Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery (ACMI-SATS) project seeks to restore to telerobotic surgery, many of the sensory and kinesthetic cues available in open surgical procedures. This improves the effectiveness of tele-surgery by allowing a surgeon to utilize tactile, spatial audio and three-dimensional visual cues as well as meaningful proprioceptive and kinesthetic information

**Description of the methods:** The Florida Institute for Human and Machine Cognition (IHMC) developed the ACMI-SATS system with both simulated and actual surgical robot systems. It provides an integrated architecture with a wide field of view pseudo-three dimensional visual operative field, surround sound for spatially relevant audio when selecting instruments and multiple tactile interfaces that represent instrument dynamics. ACMI-SATS provides a natural free motion control interface that uses a wearable, wireless motion-capture system to track head, torso, arm, wrist and finger movements. Natural motions drive the movement of the robotic instruments and the endoscope. The surgeon can stand or sit without any external restrictions and proprioceptive and kinesthetic sensations map to the visual presentation at a 1:1 scale. Motion capture enables gestural control to manage mode changes (such as clutching or switching control to a different arm).

**Preliminary results:** Initial evaluations on the ACMI-SATS testbed indicate that novices (non-surgeons) can learn to control and manipulate the robotic end effectors to perform minimally invasive surgical training tasks in simulation quickly and with low cognitive effort.

**Conclusions/Expectations:** The sensory interfaces augment understanding by providing additional information to the surgeon intuitively without overloading visual or auditory sensory channels. The motion-capture and gestural control interface allows the surgeon to use more natural, unrestricted movements control robot actions and mode changes. By mapping the visual scale directly to motion of the arms, the surgeon can maintain awareness of instrument positions even when they are no longer with the endoscope field of view. ACMI-SATS can be integrated with any surgical robot platform and could allow surgeons to learn and perform more procedures in a given time frame, with less effort and with fewer surgical errors.



## **Appendix 2: Acronyms**

ACMI-SATS - Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery

AMI - Adaptive Multiagent Integration

BMI - Brain-Machine Interface

BORIS - Basic Operational Robotics Instruction System

DARPA - Defense Advanced Research Projects Agency

DoD - Department of Defense

ERF - Electro-rheological fluid

fMRI - Functional Magnetic Resonance Imaging

FSM - Finite State Machine

GUI- Graphical User Interface

HAPsMRT - High Altitude Platforms Mobile Robotic Telesurgery

HD - High Definition

HMD – Head Mounted Display

HMI- Human Machine Interface

IED - Improvised Explosive Device

IHMC – Institute for Human and Machine Cognition

NASA - National Aeronautics Space Administration

SA - Situation Awareness

SAGES - Society of American Gastrointestinal and Endoscopic Surgeons

TSAS - Tactile Situation Awareness System

UAV – Unmanned Aerial Vehicle

VE - Virtual Environment

VR - Virtual Reality